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An Investigation into the Capability of Civil Satellites to Support Selected Operational-Level Imaging Requirements.

by

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A paper submitted to the faculty of the Naval War College in partial satisfaction of the requirements of the Operations Department. The contents of this paper reflect my own personal views and are not necessarily endorsed by the Naval War College, the Department of the Navy, or the Department of the Air Force.

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ABSTRACT

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This paper examines the degree to which two hypothetical operational level imagery collection requirements can be satisfied by current and future civil imaging satellites. It is asserted that the operational level commander is singularly bereft of imagery surveillance resources keyed to his unique theater perspective and that civil satellites may contribute to derived shortfalls. The intent is to familiarize the reader with the resource and to generate thought regarding potential use of the civil systems to support operations. Necessary background information on the systems is provided and an analytic framework is developed. Key characteristics of the requirements in terms of imagery quantity, quality and timeliness are evaluated against sensor performance specifications. The outcome suggests that integration of civil systems into operations is not a panacea. However, they are an essentially untapped resource which present advantages in performance, cost, political issues and near term benefits when compared to more traditional solutions to unfulfilled requirements.

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INTRODUCTION

Operational art as a separate and distinct level of warfare requires a perspective unique to its position between strategic and tactical war fighting. Tasked with the mission to create the necessary conditions which allow subordinate commands to conduct operations in pursuit of aims identified by the National Command Authority, (NCA) the theater commander necessarily has intelligence needs different from either level, yet having elements of each.

NCA intelligence needs are much broader in scope than is an operational commanders prior to and during war. The NCA is interested on a global scale about potential enemies and allies political motivations and intent. Is the enemy mobilizing? Does he have weapons or advantages which will result in overwhelming technological surprise to the nation's forces at the strategic level? What allies will support the enemy? Given answers to the above, the NCA determines its policy and decides whether to commit forces based on national interests and force capabilities.

The theater commander's requirements differ in terms of physical and temporal constraints. He requires information which will allow him to plan the campaign resulting in the success of the joint force mission. Instead of determining what needs to be done; stop aggression, restore rightful government, etc, he will concentrate on how to accomplish the mission designated by the NCA.

Unlike the tactical commander who can react quickly to unanticipated shifts in the flow of battle with forces reserved for this purpose, the operational commander cannot easily or quickly alter force commitment without major penalty.

"The Operational commander must determine his line of operations far in advance." (30:3-8)

To do so he must understand the current characteristics of the entire theater of operations be it a Warsaw Pact Air-Land Battle scenario, the Persian Gulf or much smaller theaters such as the Falklands, Panama or Grenada. The tactical commander is concerned with a much more localized area of operations.

In addition to broad area geographic characteristics, the operational commander requires current intelligence on the disposition of enemy forces theater-wide in order for him to apportion his forces properly against the most important threats to the campaign. He must have a clear picture of major opposing force dispositions in relation to each other and to the overall theater in order to deduce the intent of the opposing commander and plan accordingly. He is primarily interested in those enemy forces of a size or capability which, due to their mobility or destructive power, can influence a phase of his campaign.

Typically, such force sizes would be division level or higher, but due to special capabilities or advanced weapon systems could include lower levels or organization as in the case of the Iraqi Republican Guards armed with T-72 tanks. The lack of knowledge of such a force's current position within a theater spanning hundreds of thousands of square kilometers (SqKm) could severely inhibit planning and ongoing operations. The need for information regarding relationships of major opposing forces over broader theater areas over short time frames as well as current geographic characteristics is unique to the operational level and will be labelled synoptic in nature.

Operational requirements are broader than those associated with tactical preparation of the battlefield and are certainly much more detailed than that of the NCA.(30:3-9) Portions of the requirement may be satisfied by several disciplines including Humint, Sigint, etc. However, the synoptic nature of the problem requires essentially a snapshot or composite image of the area of responsibility (AOR) within a short period of time. Only imagery intelligence (Imint) can provide a definitive assessment of both geographic characteristics of the theater as well as <u>precise</u> location and identity of opposing forces of interest to the theater commander. It is the need for Imint at the operational level which will be the focus of consideration herein.

The remainder of this paper will be devoted to the explanation of operational imagery shortfalls and the reasons for their continued existence. This will be followed by an analysis of Civil imaging satellite potential for contribution to defined shortfalls including the limitations, scope and technique for evaluation. A short overview of Civil imaging satellite technology and capabilities will be provided, followed by the analysis of their potential to contribute to the selected requirements. The remainder will compare this potential solution to others and finish with conclusions and recommendations.

COLLECTION SHORTFALLS

It is interesting to note that it is the NCA and tactical levels which are best furnished with sensors tailored to their respective roles. We must speculate that the NCA has adequate resources to perform necessary global intelligence functions. Although probably shared when appropriate, it is unlikely they would be "chopped" to subordinate levels for exclusive local use in theater. The NCA role is global and there are ongoing responsibilities beyond a particular theater preventing dedicated use to any particular one.

We will assume for the purpose of this paper that an operational commander cannot depend on his needs consistently out-prioritizing those of the NCA. Under that assumption, strategic capabilities are of limited use to him on a day-by-day basis for the synoptic imaging requirement.

The tactical level is relatively rich in all sorts of reconnaissance platforms. These include the TR-1/U-2, RF-4,14,16, and 18 aircraft as well as many others capable of handling a variety of imaging sensors. These sensor systems are generally adequate to support division/wing/task force operations (although there are never enough), but are inadequate to fully support the synoptic needs at the operational level. These shortfalls are due to the physical design limitations of either the platform or the sensor. The range of the aircraft or sensor collection capacity are not adequate to cover significant fractions of the operational (AOR) in a reasonable period of time and number of missions. In addition, these airbreathers are vulnerable and generally too precious to risk to obtain necessary information concerning deep forward areas. Such systems would have to repeatedly map broad areas searching for low density, dispersed targets deep within theater areas while at great risk. The TR-1/U-2 which has the greatest area coverage capability is slow and vulnerable to surface-to-air missile attacks. The SR-71 and associated sensor subsystems most closely match the vulnerability and collection criteria of the synoptic mission. The aircraft has, however, been mothballed due to political, fiscal and degrading survivability, (8:39) and is unlikely to see widespread use in the future. The JSTARS system, a potential replacement, is not yet in produciton while it faces a tenuous funding forecast due to its cost, vulnerabilities and the overall reduction in available money. (13:25) Much data for operational requirements must be available prior to initiation of hostility. It is likely that any of the above systems penetrating deep sovereign airspace during a crisis would cause undesirable escalation even it they were not vulnerable.

Given the foreseeable lack of reconnaissance systems organic to the operational level, the limitations of tactical systems to satisfy operational requirements and the presumed non-availability of dedicated strategic systems for these purposes, it follows that important operational intelligence requirements currently and will continue to go unsatisfied. Independent evidence for the existence of such gaps is the money and time spent on the development of systems such as the national aerospace plane and the "lightsat" family. To the extent possible, these are justified by the need for supplemental or surge intelligence collection capacities over crises areas. (23:70)

The continued existence of this gap is due in large part to the lack of cohesive thought and writing about intelligence needs specific to operational art. Since it si difficult to distinguish even amongst "warfighters" exactly what operational art is, it should not be surprising that individuals responsible for budget decisions do not recognize it and certainly do not recognize the need and will not pay for intelligence assets unique to it.

Decision makers have had an overwhelming predisposition toward solving the Warsaw pact problem and have planned and implemented collection systems without consideration of the generic operational level problem outside of that theater. This is typical of a Washington "beltway" mentality which biases development toward the strategic end of the spectrum while presuming or claiming that such systems will accommodate other needs.

Tactical systems are funded because of their relatively small costs and contribution to a well-recognized level of warfare. There is a broad basis of advocacy for such systems while an "advocacy vacuum" exists for operational-level needs. Systems tailored to satisfy operational requirements do not compete well against tactical or strategic assets for these reasons.

Other reasons for continuing shortfalls in imaging capability at the operational level include the military predisposition for elegant, high-tech and therefore costly solutions to problems, the perception that a capability must be organic and a failure to consider external alternatives because of the not-invented-here mentality.

In spite of these biases a solution to the synoptic collection shortfalls must be found. The solution must fit within the severe fiscal environment anticipated and be capable of contributing to the need as early as possible. Because of the potential disapproval for use of airspace even by a friend, the risk and potential for escalation caused by flights over enemy territory, a space-borne platform is desirable.

I believe that such a niche can be satisfied or at least significantly contributed toward by the array of civil imaging satellites currently flying or being planned for the near future. It is the purpose of this paper to ignore the biases described above and perform an objective assessment of these systems capability to contribute to a small subset of operational-level imaging requirements selected for that purpose. These requirements are intentionally severe necessitating the collection of a large amount of imagery in short periods. The intent is to provide a critical analysis which would cause the reader to consider the relatively untapped civil satellite resource as a potential contribution to the requirements within or others beyond the scope of this paper.

LIMITATIONS

This analysis is necessarily performed at the unclassified level since many relevant official documents/statements are highly classified or compartmented. Operational-level requirements are not clearly identified in writings so those identified herein are derived from available sources by the author and are therefore hypothetical in nature. Even so, it is my belief that they are rational and representative of true needs because of efforts to make them so via the author's intelligence experience and discussions with local and field-deployed experts.

Judgements of systems' capability are based solely on comparison of system performance specifications to assessed requirement satisfaction. The only way to be certain of performance is to examine the imagery (28:98) under actual operational conditions. Without the resources to purchase/reproduce large amounts of imagery or attempt to utilize it under battlefield conditions our conclusions are academic in nature and warrant additional, more realistic testing.

This paper will focus on imagery intelligence only, though it is anticipated that teaming with Signals Intelligence would magnify any contribution of the imaging systems.

METHODOLOGY

The analysis was accomplished by first identifying unsatisfied requirements generic to the operational level. This was done by reviewing case studies within the NWC operations course emphasizing the Falkland and Grenada affairs and also including Just Cause and Desert Shield. Due to time and space limitations the identified requirements were down-selected in quantity. An evaluation was then made of Civil satellite systems potential by comparing requirement parameters to available system performance specifications in terms of quantity (area covered), quality (resolution), and timeliness (delay between need and availability). Because of the severity of the identified requirement, there will be some discussion of alternative solutions within the Civil satellite constellation and a brief comparison of pros and cons of operational implementation of these compared to more traditional ways of doing business in DOD. This paper will illustrate representative examples of Civil Satellite contributions not provide an exhaustive study of all possible requirements.

REQUIREMENTS

The theater commander is responsible for coordinating all normal intelligence collections activities in his area. (32:4-2) He must insure that collection is responsive to the needs of the component commands as well as those of the unified command. This burden spans an extremely wide spectrum of military, political, economic, scientific and sociological needs.

Major collection gaps confront the commander given the task of initiating operations particularly if the operations will take place against an unfamiliar opponent in a remote area such as Urgent Fury, the Grenada rescue or Corporate in the Falklands. Background information on the operational area will be available but such information is often general in nature and dated. The U.S. forces in the Persian Gulf were well acquainted with Iraqi Orders of Battle (OB), however, the locations and dispositions of units after the invasion of Kuwait across the theater was much less certain. The location of key combatant forces such as the Iraqi Republican Guard changes over time as they consolidated defensive positions as the Allied threats and intent became more clear.

In general it can be determined that a force vacated or entered a specific area under surveillance, it is much more difficult to track such a force as it redeploys to new areas.

Though there is a multitude of Air, Naval and Ground order of battle tasks, this analysis will be restricted to the severe requirement to monitor the locations or disposition of brigade or larger ground forces throughout the theater. The timeliness requirement for current intelligence on brigade level movements will be set as the need for synoptic theater coverage every 24-48 hours. This coverage should be of sufficient quality to identify the type of equipment associated with the emplacement in order to determine the character of the deployed unit. (Armored, mechanized infantry, etc.) Current theory (Fig. 1) requires resolutions between 0.6 and 1.5 meters to perform this function for a single vehicle. The requirement is to detect the presence and characterize the nature of a Brigade-level force which is an entirely different function than the task of identifying an individual vehicle. Utilization of contextual cues such as likely location for deployment, grouping of vehicles and use of camouflage will affect the actual resolution necessary to perform this task, potentially mitigating this severe resolution requirement. Nevertheless, this specification will be retained for our illustrative purpose.

The size of the area over which this must be accomplished is also critical due to the direct trade between amount of area possible to be covered and resolution quality. The higher the resolution, the smaller an area a system can collect.

In Desert Shield/Storm, the commander will want to be aware of opposing-force disposition changes over the entire theater. This would include much of Iraq and all of Kuwait totalling roughly 251,000 SqKm. Other theaters; Falklands and Panama, may require considerably less while a European scenario would require considerably more. The Persian Gulf synoptic requirement will be considered the standard. Briefly stated, it requires the collection of 251,000 Sq Km every forty-eight hours at a resolution of about 1.6 meters. The purpose is to lead to the rapid detection of brigade-level or higher force disposition.

Another requirement facing the operational commander is to accomplish an estimate which requires full and comprehensive

Table 1. Ground Resolution

Target[a]	Detection[b]	General ID[c]	Precise ID[d]	Description[e]	Tech. Analysis[f]
Bridges	6	4.5	1.5	1	0.3
Communications					
Radar	3	1	0.3	0.15	0.015
Radio	3	1.5	0.3	0.15	0.015
Supply Dumps	1.5–3	0.6	0.3	0.03	0.03
Troop Units (in bivouac or on road)	6	2	1.2	0.3	0.15
Airfield Facilities	6	4.5	3	0.3	0.15
Rockets and Artillery	1	0.6	0.15	0.05	0.045
Aircraft	4.5	1.5	1	0.15	0.045
Command and Control Headquarters	3	1.5	1	0.15	0.09
Missile Sites (SSM/SAM)	3	1.5	0.6	0.3	0.045
Surface Ships	7.5–15	4.5	0.6	0.3	0.045
Nuclear Weapons Components	2.5	1.5	0.3	0.03	0.015
Vehicles	1.5	0.6	0.3	0.06	0.045
Land Minefields	3–9	6	1	0.03	0.09
Ports and Harbors	30	15	6	3	0.3
Coasts, Landing Beaches	15–30	4.5	3	1.5	0.15
Railroad Yards & Shops	15–30	15	6	1.5	0.4
Roads	6–9	6	1.8	0.6	0.4
Urban Areas	60	30	3	3	0.75
Terrain	—	90	4.5	1.5	0.75
Surfaced Submarines	7.5–30	4.5–6	1.5	1	0.03

a. Chart indicates minimum resolution in meters at which target can be detected, identified, described, or analyzed. No source specifies which definition of resolution (pixel-size or white-dark) is used, but the chart is internally consistent.
b. Detection: Location of a class of units, object, or activity of military interest.
c. General identification: Determination of general target type.
d. Precise identification: Discrimination within target type of known types.
e. Description: Size/dimension, configuration/layout, components construction, equipment count, etc.
f. Technical analysis: Detailed analysis of specific equipment.
Sources: Senate Committee on Commerce, Science, and Transportation, *NASA Authorization for Fiscal Year 1978*, pp. 1642–1643, and *Reconnaissance Hand Book* (McDonnell-Douglas Corporation, 1982), p. 125.

Figure 1: Theoretical resolution necessary to accomplish a variety of military tasks. (11:98)

understanding of the current characteristics of the area of operations. Such information is generally included in maps, if available, but these are often not current. In extreme cases such as URGENT FURY, Admiral Metcalf initially had only a chart of Grenada dated from 1895. (31:293) While it is the exception for maps of such poor quality to be the only source of data available for planning and conducting combat operations, it is by no means certain that future operations will have current maps. DMA states that non-emergency updating of maps will require a minimum of two years given a high JCS priority and availability of imagery. (7:1) A surge capability exists to produce updated maps but it is limited in nature and also dependent on availability of imagery.

A need therefore exists to provide the operational level with very current imagery of the AOI in order to support development of MC&G data for planning. The imagery must be capable of displaying the physical characteristics of the area of interest to the commander. It must also support the rapid processing from raw imagery to appropriate mapping products.

The data must be current and if possible, illustrate the effects of climatic conditions such as vegetation, soil moisture, snowfall, etc. Because the planning perspective is broader than the area actual operations are being conducted within, the area requirement will be estimated at 500,000 SqKm. The timeliness requirement is much less severe and must accommodate mapping product production time. It will be set to allow encompassing current seasonal variation with a collection window of 1 month. Finally, resolution requirements for the broad areas will be set at 30m because there is a precedent for use by Desert Shield of this quality data. (36)

IMAGING FROM SPACE

The capability to observe and evaluate the ground from remote platforms has evolved from both the technical standpoint as well as scope from the realm of the pure military to that of the civil sector. Utilizing the unique perspective of space platforms, the civil community has begun to take advantage of satellite platforms and advanced sensors to satisfy a wide variety of needs. A basic understanding of imaging from space is necessary in order to appreciate civil sensor capabilities.

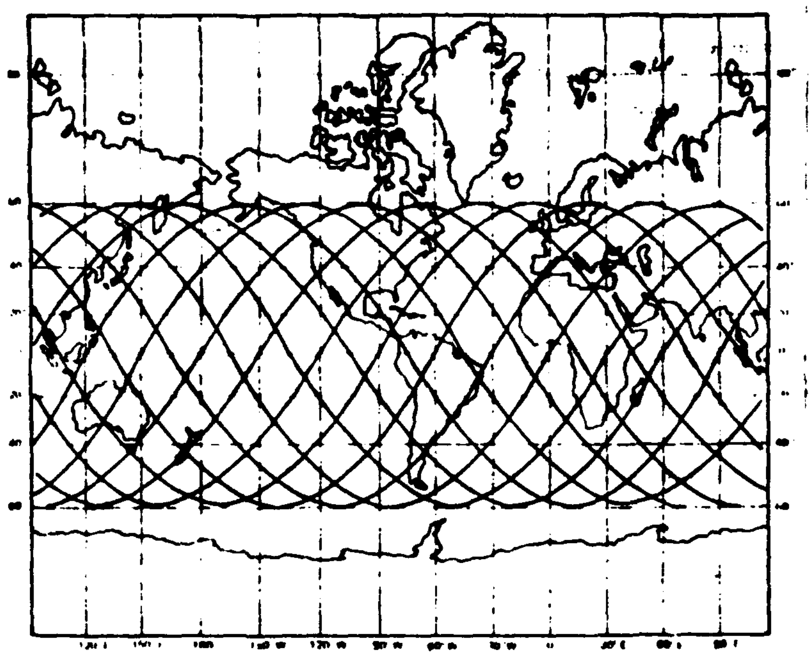
Sensor capabilities are influenced not only by their specific design, but by their orbit. An equivalent sensor in near earth orbit can image at better resolution than the same sensor further away. Conversely the near-earth sensor with the same angular field of view as that in higher orbit can observe only a much smaller area. There is therefore, a direct tradeoff between resolution, area coverage and orbital altitudes. Most civil sensors opt for orbits between 500 to 700 Km providing moderate resolution and wide fields of view.

Resolution is a term used to describe the quality of the image or an indication of the capability to discern the presence of objects. A ten meter resolution indicates the capability to discern two objects of equal intensity against a contrasting background when they are 10 meters apart. Closer than 10 meters the objects will appear as a single "blob". (15:47) Resolution depends on the quality and design of the satellite optics, the orbital distance, contrast of the objects in the scene, satellite stability and atmospheric conditions. Other factors such as the target reflectivity, size, shape, and background are key determinants. It is important to note that the capability to perform a particular job is very situation dependent and cannot be expressed solely as a single resolution specification.resolution.

Generally, the plane of orbit is fixed, and due to the rotation of the earth beneath it, a satellite does not follow the same ground trace every orbit. Most civil systems can image only the area directly beneath them (termed the satellite nadir). This combination results in the necessity to wait for some period for the orbit to return or precess back to the origination point for the satellite to view a spot seen previously. This period is called the revisit rate. It is fixed for a specific system but generally varies between 2 and 20 days for typical civil systems. Revisit can be set by carefully controlling launch inclination, orbital ellipticity and altitude. Figure 2 illustrates the ground trace of a single satellite over several orbits.

The above terms, resolution (quality), area cover (quantity) and revisit (timeliness) are the key determinants of the system capacity to perform a mission. These are all carefully determined by the builder based on intended mission and funds available. Civil missions we are interested in produce image quality of between 5 and 100 meters resolution, revisit between 2 and 20-plus days and can image a swath about 100 Km wide.

There are two basic types of imaging systems, film and electro-optic. Film systems like a camera, record images on light sensitive emulsion bonded to plastic which must be returned to earth for processing. This is a distinct drawback because of the time necessary to de-orbit and process the film as well as the inconvenience of running out of film with the corresponding cost of launching another satellite for more imagery.



<u>Figure 2</u>: Ground trace of a single satellite over 12 orbits.

These problems have been overcome by electro-optic imaging. Essentially video frame cameras in space, they use tiny sensors called pixels to measure the amount of light returning from a given spot within the intended scene. This measurement is assigned a digital value which can be transmitted to earth where the image can be reconstructed almost immediately. This of course speeds the process as well as eliminates the limited-film problem. The "digital" scenes can be computer-enhanced to bring out detail not available to the eye or film, but captured by the extremely sensitive pixels.

The down-side of this technology is the need for very high capacity downlinks (100 megabits/sec or greater) adequate computer systems and the skilled technicians to operate them. The better the resolution of the system, the greater the amount of data or number of pixel values which must be transmitted for a given area covered.

Pixels can be designed for sensitivity in specific bands of the electromagnetic spectrum. Banks of pixels, each with their own spectral sensitivities can be included in a single satellite. This is important since many objects of military interest have strong, unique signatures or reflective characteristics outside the visual range. (1:5)

A pixel value corresponds to the average amount of light within its sensitivity range reflected by the area on the ground from which light is collected. Because this is an average value it will be affected by all objects within the area from which light is collected. A pixel value measuring an area containing an object of interest will generally be different than a value from an adjacent pixel without such an object. The degree of difference is based on the intensity of the object's signature, its chemical makeup, the percentage of the pixel occupied by the object and the consistency of the background between the pixels. (1:7) An example could be camouflage which looks identical to its background in the visible spectrum but due to its unique reflectance properties contrasts greatly from its background in other regions of the spectrum. These contrasts are often strong enough to influence a multiband system signature within a pixel even though the object is much smaller than the area covered by the pixel.

These differences are often much more subtle than the unaided eye can detect especially for isolated pixels within a large scene. Nevertheless, they exist and can be isolated via computer processing. The problem of characterizing the effect as produced by an object of interest can be accomplished by comparing the signature to a library of known signatures previously collected and looking for a match. The accuracy of this process is determined by the factors discussed above as well as the number of spectral bands measured. Unfortunately, the more bands utilized, the more data must be transmitted and processed.

Since much more area can be covered per pixel value transmitted by lower resolution systems, it is greatly in the favor of the operator from an efficiency standpoint to perform the detection functions at lower resolution using multiple bands than to collect a single band at high resolution.

Civil satellites collect three basic types of imagery. Optical or visual wavelength imagery is most common. Multiple-band or multi-spectral data is most useful because of the unique signatures capable of being sensed. Finally, synthetic aperture radar imagery is becoming more common. This is due to the capacity of this type system to image at night and through weather. These features enhance the system revisit capacity and make imaging more reliable.

A disadvantage of radar satellites is their need for higher on-orbit power sources than "passive" optical systems. This adds to their complexity and cost. Radar imagery is also the least literal of the imaging types. It is therefore poorly understood and rarely utilized except by those who possess correct interpretive and analytic skills.

CIVIL SATELLITE IMAGING SYSTEMS

Civil imaging satellite systems owned and operated by a variety of countries represent a potentially valuable resource for utilization by the U.S. military. These systems, intended to gather information on a wide range of civil planning and investment topics, can and have been utilized to observe scenes of military interest, including Chernobyl, the Iran/Iraq War and Soviet Northern Fleet areas. (11:97-99) Currently flying sensors with the potential to contribute to the stated requirements are described below followed by a description of systems planned to be available by mid-decade.

CURRENT SYSTEMS: U.S.

Landsat, the first civilian land remote-sensing satellite, was launched by the U.S. in 1972. (11:100) A digital system, Landsat is capable of downlinking data to eighteen sites worldwide including one in Riyad, Saudia Arabia. The principle sensor called a thematic mapper can simultaneously collect six discrete spectral bands with a 30 meter resolution producing images about 180 Km on a side. (5:162) A single Landsat revisits points on the earth every 16 days. Algorithms for isolating signatures of interest from the multispectral (MS) data have become extremely sophisticated. Landsat-6, the next satellite, will include the capabilities of its predecessors plus a 15 meter panchromatic visible band. The configuration of Landsat-7 is uncertain at this time. (35:529)

Two satellites, Landsat-4 and 5 are currently operational. Landsat-6 is scheduled for 1991 launch. Spacecraft availability and funding for future operations are open issues which must await near term decisions from the U.S. Space Policy Board. (12:89)

CURRENT SYSTEMS: FRANCE

SPOT, launched in 1986 by France is a digital imaging satellite with a multispectral resolution of 20 meters and a visible resolution of 10 meters. The satellite can collect a 117 Km wide swath and has an orbit repetition period of 26 days. Unlike LANDSAT which can image only directly below the satellite, SPOT uses a rotatable mirror to collect off-nadir imagery. This capability enhances its revisit period to 4 days as well as significantly increasing local area coverage. (27:15)

If SPOT-3 is launched this year and two satellites orbit simultaneously, system collection rates and revisit will improve. Reports persist that SPOT can actually image at resolutions approaching 5 meters rather than its advertised 10 meter best. (11:102) Because of the military significance of current SPOT data and potential political ramifications from its use, the French have ceased the sale of data from the Persian Gulf area.

CURRENT SYSTEMS: USSR

In 1987 the Soviets announced that they would sell imagery as good as 5 meters resolution of any non-socialist country. (35:537) They fly three classes of satellites, one of which, Resurs-F is a film-based visible system capable of 5-10 meter resolution. Resurs O is a 3-band multispectral system capable of 30 meter resolution and an 85 SqKm swath. Radar-Cosmos is a radar system capable of 10 to 30 meter resolution.

The Soviets have indicated that they are building a 2 meter resolution capability and that Resurs O will be digital-downlink compatable by 1992. (35:537) The 30-40 day delivery time due to the film-based nature of the Resurs F system limits its utility to the real-time operational mission.

COUNTRY/ORG	SATELLITE PROGRAM/INSTRUMENT	SENSOR TYPE	RESOLUTION METERS (QUALITY)	PERIOD/PERSIS DAYS (TIMELINESS)
EUROPEAN SPACE AGENCY	ERS-1/AMI	SAR	30M	3 Days
CANADA	RADARSAT	SAR	10-100	Daily
CHINA/BRAZIL	CBERS	MS	19	-
FRANCE	SPOT 2/3	MS/OP	20/10	4
FRANCE	SPOT 4	MS/VIR	10	4
INDIA	IRS	MS	36	22
JAPAN	ADEOS	IR/OP	700/16	14
JAPAN	ERS	SAR/OP	18/18	44
JAPAN	MOS	MS	50	17
U.S.	LANDSAT 4/5	MS/OP	30/30	16
U.S.	LANDSAT 6	MS/OP	30/15	16
USSR	RADAR-COSMOS	RADAR	10-30	DAILY
USSR	RESURS F	OPTICAL	5-10	19
USSR	RESURS O	MS	30	16

KEY: SAR=RADAR, OP=OPTICAL, MS=MULTISPECTRAL, VIR=VISUAL IR, O=OPERATIONA

FIGURE CIVIL SATELLITE CAPABILITIES SUMMARY

Figure 3: Compilation of selected civil satellite performance specifications.

WATH M QUANTITY)	ORBIT TYPE	GENERAL LAUNCH
9	98.52	Pre-94
00 km 2 Total/Day	98.6	94
80	SUNSYNCH	92
117	SUNSYNCH	0
117	SUNSYNCH	-
74	SUNSYNCH	Pre-94
-	SUNSYNCH	94
75	SUNSYNCH	92
200	SUNSYNCH	Pre-94
185	SUNSYNCH	0
185	SUNSYNCH	91
90	71.9	0
-	82.6	0
85	SUNSYNCH	0

FUTURE CAPABILITIES

Several countries or consortiums are planning to field new sensors within the next few years. The European Space Agency is planning on launching ERS, a 30 meter Synthetic Aperture Radar satellite. It will revisit every 3 days and will be capable of collecting a 99 Km swath and feature a real-time digital downlink. (35:517)

Canada will launch a similar radar satellite with a variable 10 to 100 meter resolution by 1994. It will downlink up to 100 Sq Km of imagery per day. (35:521)

China and Brazil will jointly fund and develop CBERS for a 1992 launch. A five band multi-spectral system, it will be capable of 11 meter resolution. (35:521)

India will launch IRS, a 4 band multi-spectral system in 1992. Capable of 36 meter resolution, it will have a 74 Km swath width. (35:524)

Japan is planning on launching three imaging satellites by 1994. ADEOS will be a 16 meter resolution digital visual system. ERS-1 will have an 18 meter resolution SAR as its primary sensor. MOS-1b, a 4-band multispectral system will be capable of 50 meter resolution. (35:527)

All told, there are 4 digital satellite systems operating continuously today that may be of significant utility to the operational missions described. By 1994 an additional seven satellite systems are due to be fielded, including three SARS which can provide night-time and poor weather imagery. Other systems are being conceptualized such as Media SAT and a huge host of sensors necessary for the Global Change Initiative and NASA's "Mission to Planet Earth".

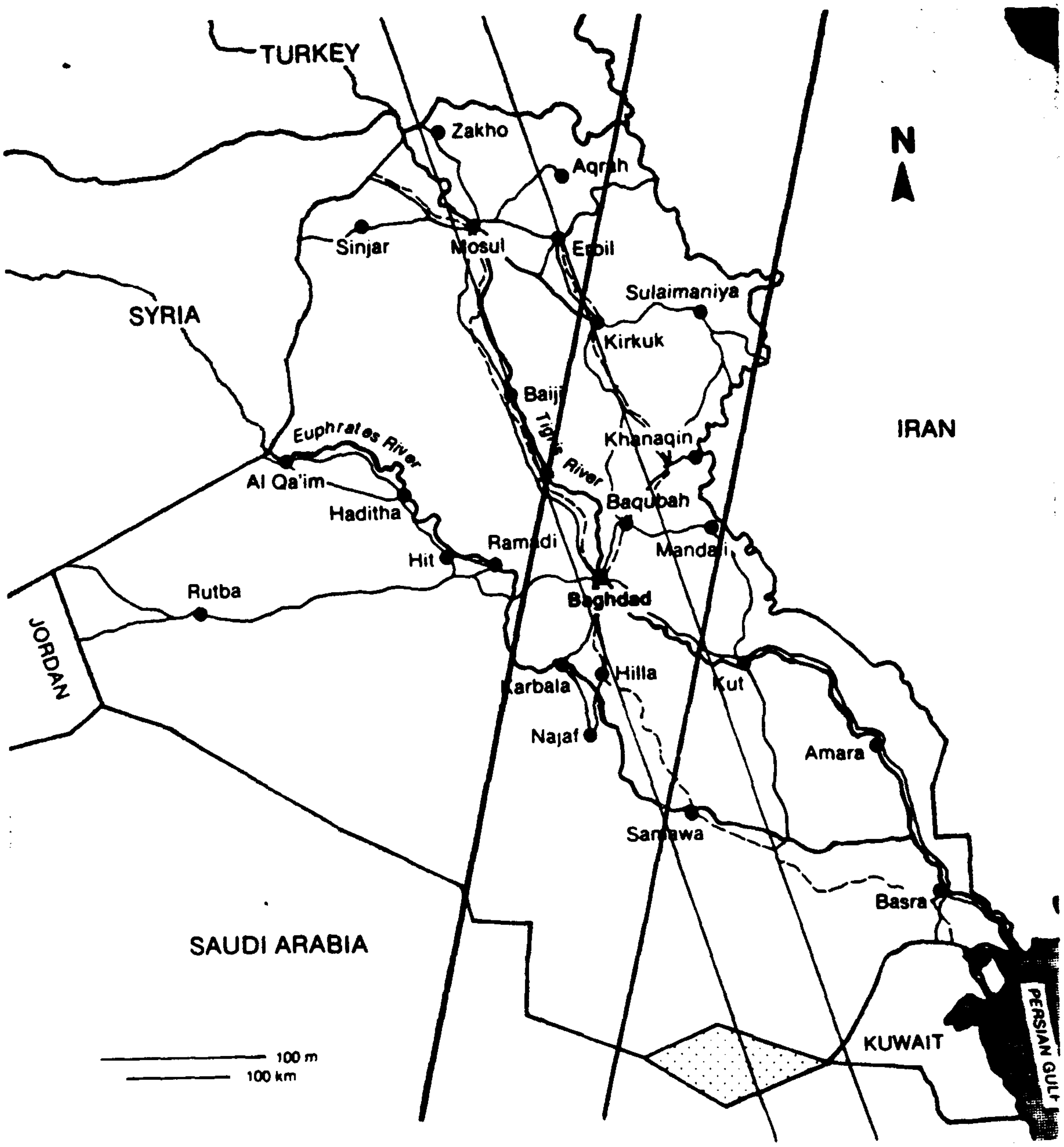
ANALYSIS REQUIREMENT 1: SYNOPTIC, HIGH RESOLUTION

The need for comprehensive knowledge of the location and characteristics of all sizeable ground force groups potentially deployed over tens of thousands of SqKm is a daunting one. No single system evaluated is capable of fully satisfying this requirement even in a dedicated mode.

CURRENTLY FLYING SENSORS

The revisit capability of Landsat is once every 16 days per satellite. With two operational satellites this period is reduced significantly to 8 days, which although greater than the 24-48 hour requirement, approaches the envelope of interest. Landsat, capable of 30 meter resolution falls well short of necessary 1.5m or better resolution indicated in Fig 1 for single vehicle detection. (Retained primarily for illustrative purposes as a standard in the introduction, Fig. 1 was produced using visual optical data and for a mission substantially different than ours.) More will be said about this apparent shortfall later.

Broad area coverage is the specialty of Landsat. With each frame capable of covering over 30,000 SqKm, the system could easily cover all of Kuwait (about 18,000 SqKm) in a single frame. A single Landsat pass optimized over the Persian Gulf collection area could acquire approximately 39% of the 250,000 SqKm requirement. (Fig. 4) Similar charts, Fig. 5 , shows a Landsat pass overlaid on the Falkland "theater" and Fig. 6 illustrates a pass over Panama. A less than obvious shortfall of Landsat is its capability to image toward nadir only. The system is not therefore agile enough to collect the gaps on either side of the nadir collection. This is a common shortfall of civil satellites when



<u>Figure 4</u>: Landsat (wide) and Radar Cosmos (narrow) single pass collections over Iraq.

Figure 5: Landsat single pass collection over the Falklands.

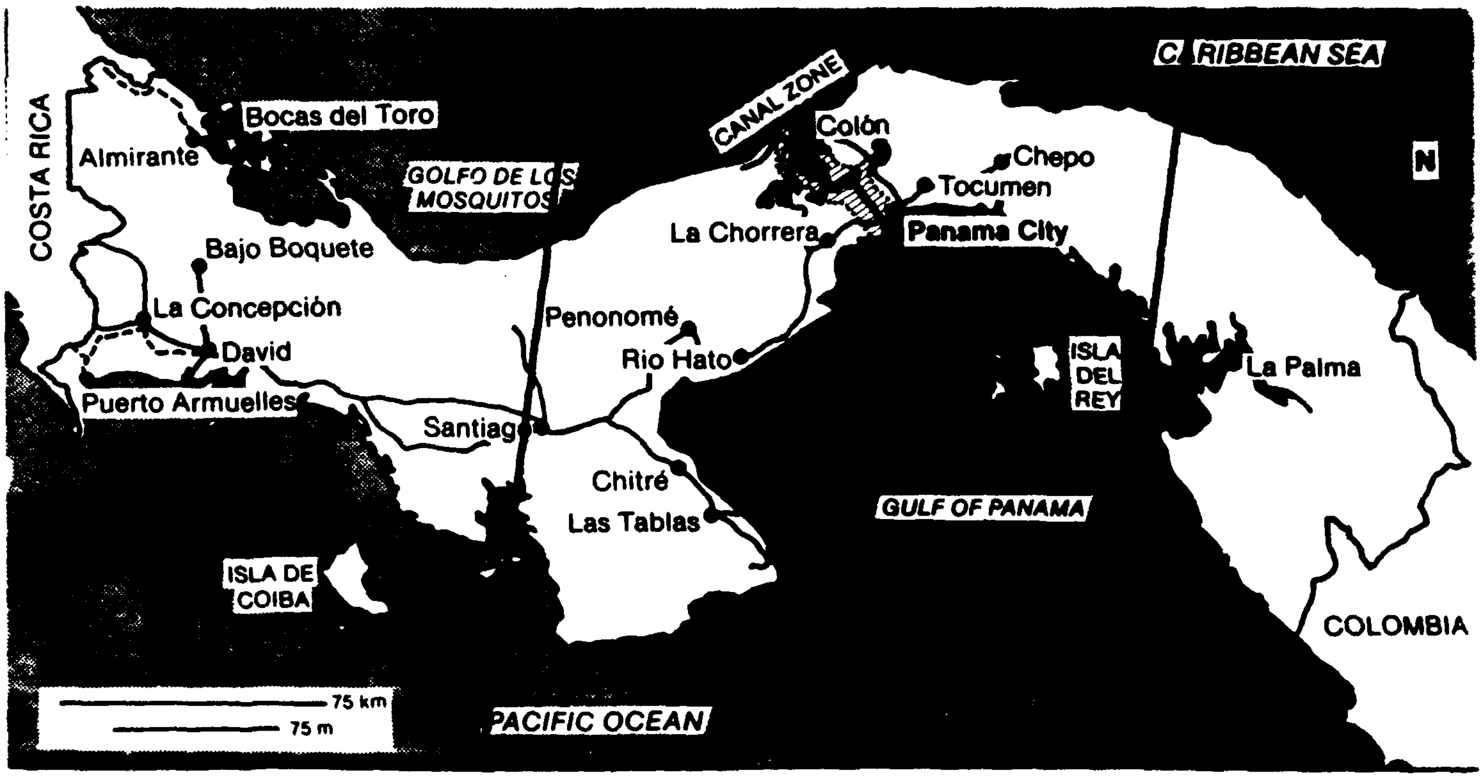


Figure 6: Landsat single pass collection over Panama.

applied to intelligence needs. Their normal customers can afford to wait for the satellite to return to the area to collect adjacent uncovered areas and have cut costs by not adding such a capability.

SPOT, a more sophisticated sensor than Landsat, can image off-nadir via a movable mirror permitting the system to revisit an area about once every 4 days and on successive passes. This is a significant enhancement to timeliness satisfaction. Capable of imaging at resolutions of 10 or 20 meters the system approaches more closely the resolution requirement than Landsat but still does not satisfy it. Also a relatively broad area system, SPOT can cover approximately 25% of the standard requirement per pass. Because of the successive pass access imaging capability there is more opportunity to fill gaps in coverage than Landsat and collect more imagery of a local area per day than if limited to a single pass (See Fig. 7).

Resurs O, the Soviet equivalent of Landsat is capable of 30 meter resolution and collecting about 18% of the requirement on a given pass. In a similar orbit to Landsat, it revisits an area about every 14 days. (5:540) Again, this system cannot satisfy the requirement alone.(Fig. 8)

Resurs F, a film-based Soviet system, has little applicability to real time intelligence issues with periodicities of days because of the delay in returning spent film. It could however, be utilized in a historical mode collecting imagery each available pass and reconstructing pertinent activity post defacto. Its use and applicability to mapping will be discounted by this requirement.

Radar Cosmos presents some unique attributes not available in previously discussed systems. Its primary advantage being relative insensitivity to weather. Because the system can image at night it need

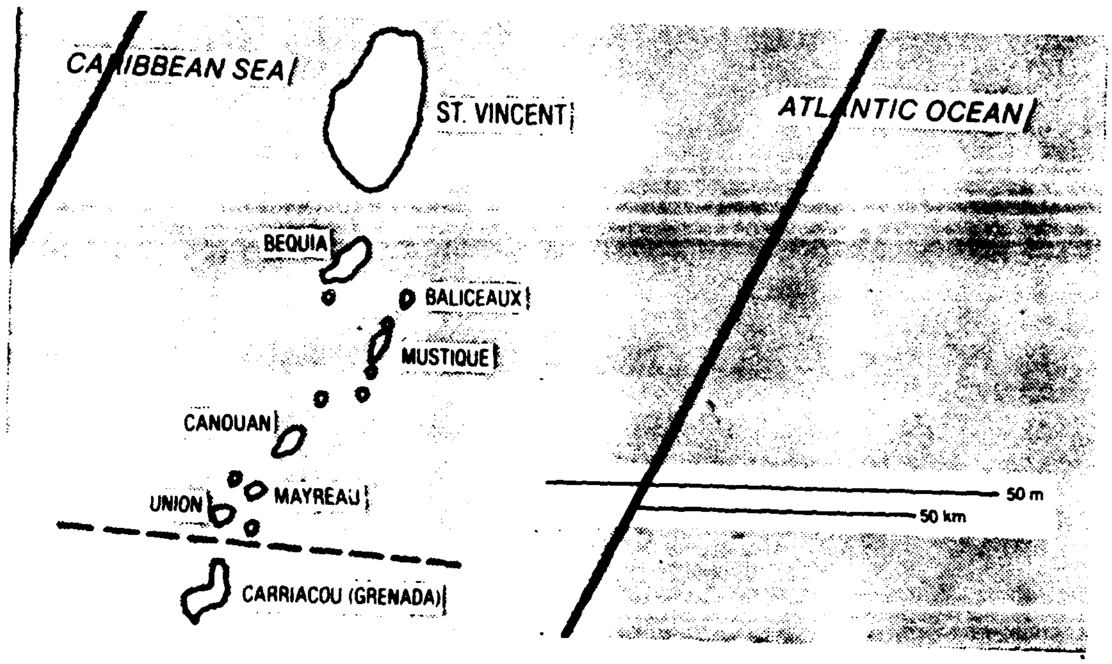


Figure 7: SPOT single pass collection over the Grenadines.

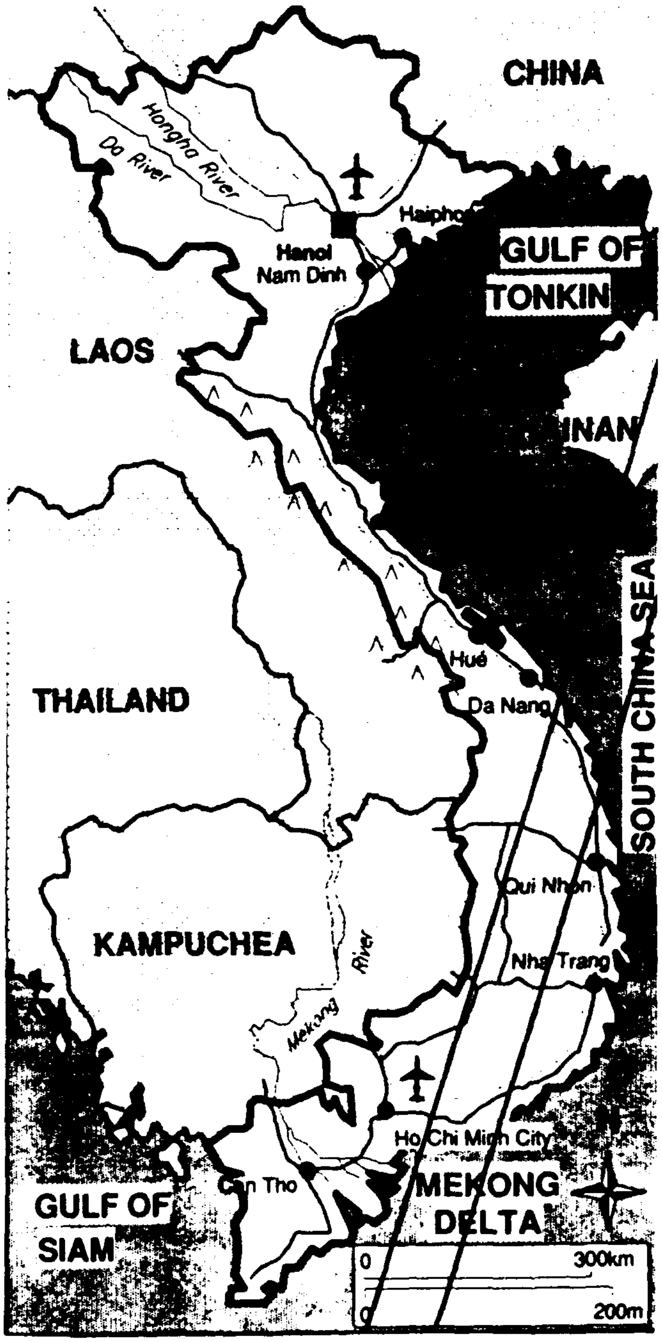


Figure 8: Resurs-O single pass collections over South Vietnam.

not be in a sun synchronous orbit. At a 72 degree orbit, the system crosses the path of the other satellites at about a 30 degree angle. It therefore offers the opportunity to fill in gaps left by other collectors. (Fig. 4) The orbit provides the opportunity for daily access to points on the ground between 72 degrees north and south latitudes. With a selectable 10-30 meter resolution the system cannot satisfy the resolution requirement. Because it is a radar its product is of a substantially different nature than the optical satellites and may not be easily compatible with them. The detectability of radar systems is widely variable depending on target material and aspect of target to the radar.

The 90 Km swath could allow imaging up to 27% of requirement. This percentage is higher than for other satellites with similar swaths because the orbit of Radar Cosmos nearly parallels the long axis of the Iraqi border. The other satellites cross the country through its short axis at about 98 degrees. A satellite's utility is therefore not only determined by its collection capability, but is situation dependent even to the extent of the orientation of the target relative to its orbit.

The obvious assessment from the above information is that although capable of contributing to the requirement periodically, the currently flying individual systems are not capable of satisfying it. Significant portions of the area of responsibility can be collected in a short time, but the imagery is not of sufficient resolution nor is obtained frequently enough. This assessment would change based on the requirements of a specific theater.

A potential solution is to consider the individual satellites as part of a single system with a large orbiting sensor suite. This concept significantly improves the revisit capability. Figure 9a shows such a suite spread over the 16 day Landsat revisit cycle optimized to evenly distribute coverage. Radar-Cosmos is not shown. The 2.2 day coverage spacing closely approaches the 48 hour requirement. Unfortunately, because the satellites are not in identical orbits, the time between revisits will change because the satellites will precess out of such a synchronization. Coverage will generally look like figure 9b. Note that there are 2 periods, days 1-3 and days 9-11 when large fractions of the area coverage (54% and 82% respectively) are met. Unfortunately, this occurs only twice over the 16 day period. While this does not satisfy the 48 hour requirement, it indicates the capability to approach coverage of the entire area of responsibility within the theater (not easily accessible to penetrators) about once per week. This is an extremely useful capability not currently available to the theater commander in near real time given our current assumptions.

The logical extension of this argument is to look ahead at the sensors planned for launch by 1994. Similar notional diagrams are provided for this new suite. They indicate that a suite synchronized for minimum average gaps (Fig. 9c) between revisits could provide significant cover about every 35 hours. Again, such a configuration is unlikely to occur frequently and there will be concentrations of cover with larger gaps appearing more like figure 9d. Figure 9d indicates the potential for nearly full satisfaction (greater than 80%) of the area quantity requirement 3 times within the period evaluated. This is a significant improvement which does not include several radar satellites envisioned for the 94 time period nor the conceptialized media SAT or a large Global Change Initiative sensor suite being considered by DOD and NASA.

Notional Satellite Accesses to a Single Area (*)

Current Systems, Optimized

Fig. 9a

DAY	0	*	1	2	*	3	4	*	5	6	7	8	*	9	10	*	11	12	*	13	14	*	15	16
SYSTEM		S			L			S					S			L			S			R		

Current systems Accounting for Precession

Fig. 9b

DAY	0	1	*	2	*	3	4	5	*	6	7	8	9	*	*	10	*	11	12	13	*	14	15	16
SYSTEM			S		L				S					S	R		L				S			

Current and Future Systems Optimized

Fig. 9c

DAY	0	*	1	2	*	3	4	*	5	*	6	*	7	*	8	*	9	*	10	*	11	12	*	13	14	*	15	*	16
SYSTEM		S			L			S		A		C		E		S		M		L			S			R		I	

Current and Future Systems Accounting for Precession

Fig. 9d

DAY	0	1	**	2	*	3	*	4	5	*	6	7	8	9	*	*	10	**	11	12	13	*	14	*	15	*	16
SYSTEM			SE		L		I			S					S	R		LA				S		M		C	

(*) L-Landsat, S-Spot, R-Resurs, A-Adeos, E-Ers, M-Mos, C-Cbers, I-Irs
<u>NOTE</u>: Chart does not include Radar-Cosmos daily accesses

Although a significant positive impact to quantity and timeliness, such improvement is not without significant downside in terms of complexity and cost. The satellites, designed individually, are not meant to be a system. The data is downlinked to widely separated ground stations. Orbits and coverages do not complement each other and as seen, will leave gaps in the synoptic requirements on either side of the orbit.

Even though the above concept makes major inroads against the quantity and timeliness requirement, resolution remains a significant problem and warrants discussion herein.

Theory states that it is necessary to sample an object two times in order to have a good chance of detecting it. This means that a sensor must have pixel sizes of five feet (ground sample distance) to detect a ten foot object. Because of this precept, systems with resolution specifications lower than that necessary to theoretically accomplish a task are disregarded as having no utility. In practice, however, objects much smaller than the ground sample distance (GSD) of a system are routinely detected by it. This occurs when the objects contrast the background, are linear in nature like roads or have unique spectral qualities as discussed earlier.

Because sensor pixels provide an average value of the individual area they sample, their values are affected by objects within their view. This is true even if the object is much smaller than the GSD, such as a 10 meter tank sampled by a 30 meter pixel. Because individual pixels within a reconstructed image are so small, the human eye cannot detect the subtle differences between the millions within the scene. Such differences are visible to the eye only when a string of pixels is affected in this manner as in the case of a narrow roadway.

The value of a pixel covering an object of interest is not necessarily unique. This is particularly true when examining only one portion of the electromagnetic spectrum. Objects of interest absorb and reflect light selectively in all portions of the spectrum, but these may not be observed directly by the eye. An object appearing identical to its background such as a camouflaged tank looks entirely different than its background in the non-visual region.(Fig. 10) The more spectral bands one examines the more likely an object's reflectivity is likely to be unique.

The example is similar to that of a sonar operator listening to a broad band acoustic environment. As he concentrates on smaller and smaller sections of the noise, he is able to break out peaks of noise caused by unique activity in the target he is trying to characterize. The more of these unique signatures he hears, the better he is able to specifically identify what makes the sounds since he can compare them to noises heard previously.

Likewise, changes to pixel values over several spectral regions can be compared to previously collected signatures to identify matches to objects of interest. Because an object smaller than the pixel can be responsible for a unique pattern of values, this process is called sub-pixel identification or characterization. (1:1)

Sophisticated computer algorithms are available which scan the millions of pixels composing each band of a multispectral scene looking for matches to known signatures of objects of interest. The performance of these routines is proportional to the area of the pixel occupied by the target. The greater percentage occupied by the object, the better the performance.

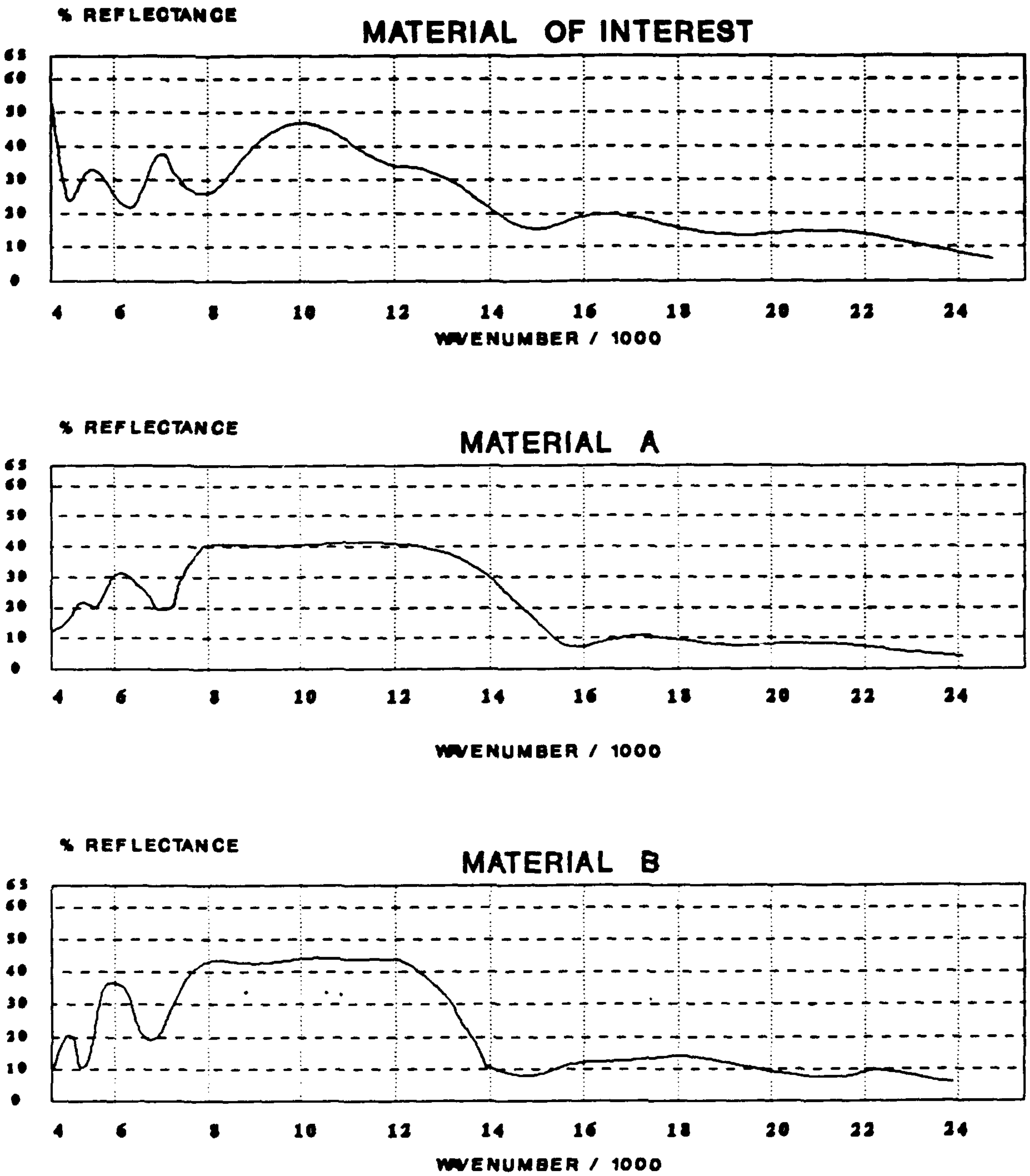


Figure 10: High resolution spectra of different materials.

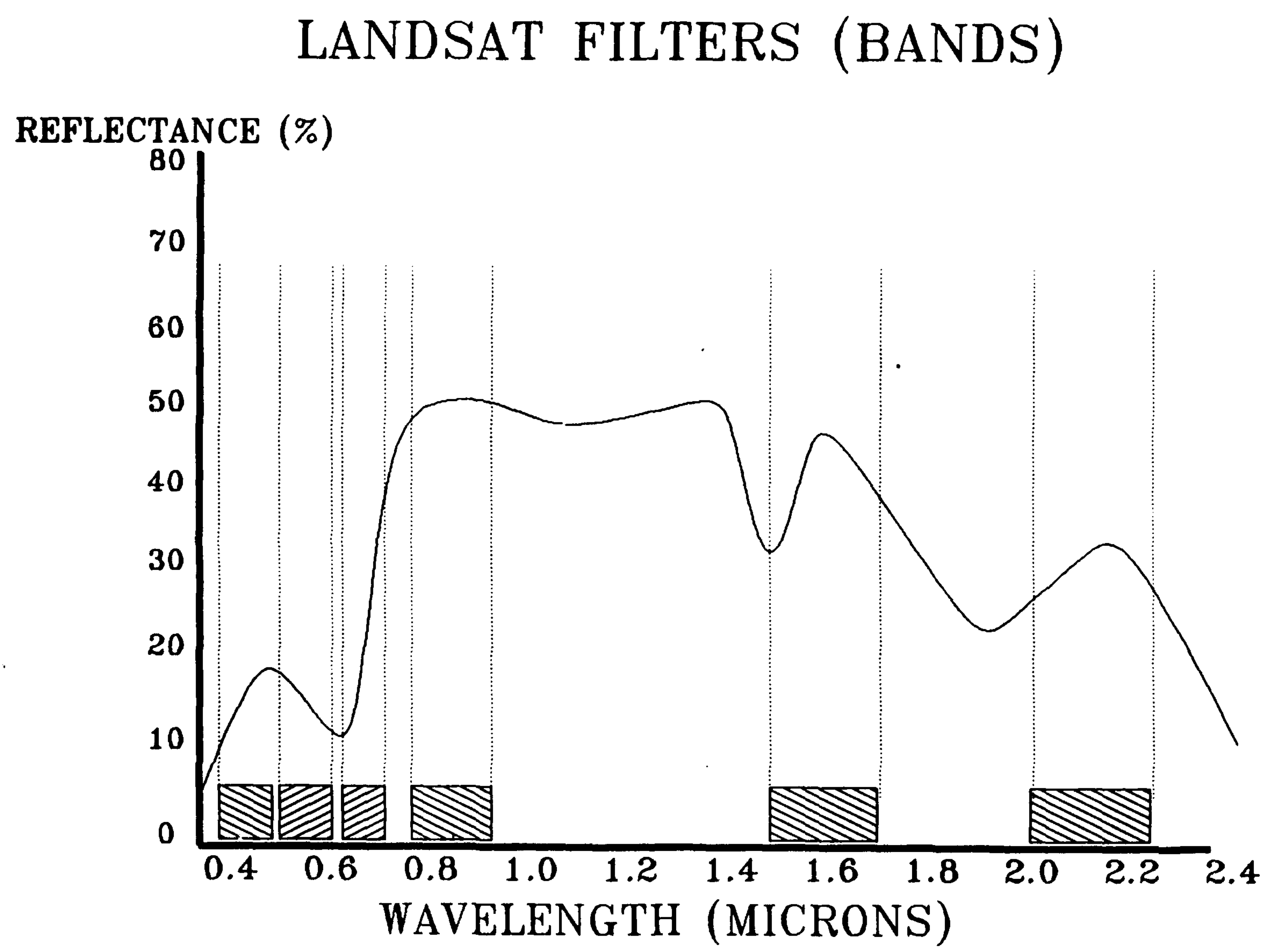


Figure 11: Landsat bandpass filters overlain on high resolution spectral plot.

An Air Force sponsored verification program utilized 30 meter GSD quality data and six spectral bands equivalent to Landsat. All targets occupying more than 22% of the 30 meter pixel were detected with a false alarm or mistake rate of less than one in ten thousand. (1:16) Tanks are not normally as large as this but their camouflage frequently is. Good detection rates can be achieved for smaller objects if greater false alarm rates can be tolerated.

Small false alarm rates are significant when looking at large areas so it is important to minimize them. Several techniques allow minimization of false alarms. One may use contextual cues to ignore false alarms indicating targets where targets cannot be such as in a lake or swamp. You may also ignore an indication if the potential target is not in a position to affect the plan under development. Isolated false alarms will probably not be of interest since we are looking for concentrations of signatures indicative of brigade-sized units. The algorithms can be "taught" or tailored to work better within a specific area such as desert or forest. A recent group of targets can be compared to past imagery. If the "hits" were there six months ago they are probably not of interest and can be ignored. Finally and perhaps most effective would be the tipping of high resolution sensors to search a small area potentially containing targets detected by low resolution systems. This would optimize the capabilities and minimize the handicaps of both sensor types allowing great resource conservation.

The point of this discussion is to suggest that the apparent resolution shortfall of the civil systems is not as dramatic as one might think upon initial inspection. The systems should therefore not be discounted for this problem, due to this apparent disparity.

SUMMARY OF SYNOPTIC REQUIREMENT ANALYSIS

The apparent diversity in resolution capability versus the selected requirement are not as great as initially perceived. The innate capacity of the multispectral systems in particular, along with demonstrated algorithms and logical assessment of the output may allow a complementary synergism with other sensors in pursuit of synoptic requirement satisfaction. While not satisfying the stated timeliness requirement, the current systems, if linked, could provide collection of the synoptic requirement frequently enough to be very useful.

Problems preventing rapid integration of this resource into operations include differences in digital formats, spectral sensitivities requiring tailored algorithms and signature data bases, lack of orbital synchronization preventing optimized collections and other technical problems such as tasking, downlinking the diverse satellite products to central locations, and rapid exploitation and product transmission to the field. Political or diplomatic problems also beset this potential solution to the problem. Governments flying the systems would have to agree to allow their use and even provide priority for U.S. purposes. (27:19)

The problems expected in operationalizing civil systems for the synoptic problem appear formidable. The issues raised in this analysis are serious but must be put in perspective. First, there is no alternative. The SR-71 has been retired and will probably not be taken out of mothballs for a number of reasons; fiscal, political and operational. There is no replacement on the horizen. (34:39) A new survivable airbreathing reconnaissance platform or NASP would be formidably expensive. Even the alternative of modifying B-2 bombers would be prohibitive due to the need and corresponding expense for passive sensor development, airframe modification costs, and Low Probability of Intercept (LPI) data transmission. A new military satellite program capable of providing theater-scale synoptic imagery in real time will probably just not happen given the current and foreseeable fiscal environment. Small-sats may be a feasible alternative in terms of cost and capability. (25:63) However, they are currently not available while presenting a host of C3, launch, integration, and other problems.

When viewed in comparison to the above alternatives with their corresponding technical, cost, and political issues, civil satellites begin to appear more attractive at least as a partial solution to operational imagery collection problems. The lion's share of cost, design and development and in some cases launch and operations have already been expended. In most cases this has or will be accomplished by other countries who are our allies. Remaining costs would be a factor favored by our National security strategy in the areas of rapid data transmission, integration of the the diverse data formats and refinement of processing algorithms. Other necessary efforts would include the diplomacy necessary to make data available on a priority basis and detailed evaluation of a final concept of operations. Perhaps the most important characteristics of the civil satellites is that they exist today and they are getting better without any U.S. investment.

Finally there is a range of solutions available which can be tailored to the available budget. These include immediate administrative provisions such as compilation and distribution of contact points for all the systems to theater command centers to complete integration of modified civil satellite payloads. This range of choices differs greatly from those few normally available to solve such problems. Improvement to this type of operational mission would not require commitment of billions and waiting years prior to any results.

ANALYSIS REQUIREMENT 2: MAPPING

Because of the innate broad area collection capabilities of the civil satellites they are uniquely suited to collect the necessary raw data for mapping purposes. Their digital nature and multispectral capability allows for extremely rapid characterization of the nature of the operational AOR. Results of such efforts can be photographically overlain on existing maps to provide the commander with current vegetation condition changes, detection of new overland routes, and even the impact of last week's rainstorm as well as a host of other needs in compact form.

Because the data is available so quickly over such a large area and is so readily processable for characteristics of importance, the process could occur frequently during the campaign providing important support to ongoing planning or the evolving estimation process.

The Defense Mapping Agency provided some of this type support to Desert Shield. (36) They were able to do so due to the recent collection of reference imagery over the AOR on account of the mineral reserves that exist there. The several month preparation period available prior to the outbreak of hostilities assisted them in this endeavor. Frequent update of these products is not being planned as the major effort is going toward update of available charts many of which were last printed in 1978.

CONCLUSIONS

Based on the analysis provided, several conclusions can be made:

The operational commander has requirements for imagery unique to his level of warfighting. Based on open sources, there are gaps in the capability of current systems to satisfy them. These requirements and gaps are generic across many recent theater operations including the Persian Gulf, Vietnam, Grenada, Panama and the Falklands.

Civil satellites can contribute to satisfaction of the stated requirements. The integration of multiple satellite systems greatly enhances the potential quantity and timeliness contribution over single systems.

There are techniques and algorithms in existence today which help allay the apparent resolution shortfall of these systems.

Digital, multispectral systems may provide significant contributions to the synoptic requirement because of the unique spectral signatures associated with targets of interest and this type system's capacity to recognize them even at lower resolutions.

The most feasible contribution to the synoptic problem by civil systems appears to be integrated medium resolution multispectral collection to search and rapidly process the data and tip-off of high resolution capability sensors for final identification if adequate characterization is not initially accomplished. This technique has the advantage of optimizing the utilization of both systems to their design.

A wide range of options involving these systems exists each with costs and implementation timelines proportional to a decision maker's priorities, patience and pocketbook.

The application of these systems to general mapping functions is well-understood. Their use for operational support in this mode is not well accepted for reasons which would not stand up to objective scrutiny. Civil systems could be a ready source of current and accurate mapping data for current and future operations.

Technical, political and fiscal problems exist with the implementation of the civil satellite concept for both requirements. In relative terms these are not as severe as those which must be accommodated by the alternatives discussed. The use of current and improved civil systems may therefore offer the best combination of low cost, suitability and early results.

Civil satellite processing, sophistication, quantity and revisit capabilities are improving without U.S. investment.

RECOMMENDATIONS

The primary recommendation derived from this analysis is to encourage consumers of imagery at the operational level to consider civil satellite system products as part of the solution to imaging shortfalls. The current existence and advent of new and more powerful collectors and analysis techniques should be viewed as an opportunity to enhance war-fighting capabilities and to cut costs of alternative measures.

The U.S. should maintain and improve its current civil capability (especially Landsat) while improving the integration of all available civil sensors into its operational support. The U.S. should consider diplomatic dermarches which would result in satellite collection priorities and civil satellite orbital synchronization optimized for mutual ally operational needs. Acquisition of reference imagery over potential trouble spots should become among the first items on a theater commander's check list especially if there is no time to update existing charts.

It is a rare situation which may allow the U.S. military to significantly enhance battlefield capability for reasonable investments in terms of dollars and diplomacy. Perhaps the most significant obstacle in doing so will be overcoming the "not invented here" or "state-of-the-art" bias which became prevalent in the U.S. military during the Reagan years. However, having to do more with less and reliance on less than a custom-built extravagance will become the norm rather than the exception in the upcoming years. Acceptance of this fact is a bitter pill better swallowed sooner than later for our own good.

BIBLIOGRAPHY

1. Applied Analysis Inc., Background and Capabilities Brochure, (AAI, Sept 1990).

2. Brodie, Lonnie, "Can the U.S. Afford to Retire the SR-71 Blackbird?", Defense Electronics, Sept 1989, P. 57-60.

3. Brown, Neville, New Strategy Through Space, Leicester: Leicester University Press, 1990.

4. Canavan, Dr. Gregory H. and Teller, Dr. Edward, "Brilliant Eyes Technology Provides Dual-Mode Viewing", Signal, Dec 1990, P. 29-33.

5. Cox, William J. and Gordon, Daniel K., The Multispectral User's Guide, Washington, D.C.: Autometric, Inc., 1990.

6. "Decaying Orbit The U.S. and France May Join Forces in Remote Sensing", Scientific American, March 1989, P. 72-73.

7. Defense Mapping Agency, Digitizing the Future, Washington, D.C.: DMA, Oct, 1988.

8. Dornheim, Michael A. "U.S. Reconnaissance Weakened by SR-71 Program Termination", Aviation Week & Space Technology, Jan 22, 1990, P. 38-41.

9. Durkin, Maj Gen Robert F., USAF, "Charting a World of All-Digital Maps", Defense, March/April 1988, P. 20-26.

10. Faugeras, O.D., Fundamentals in Computer Vision Cambridge: Cambridge University Press, 1983.

11. Florini, Ann M., "The Opening Skies", International Security, Fall 1988, (Vol 13 No 2), P. 91-123.

12. Foley, Theresa M., "Eosat Urges U.S. to Fund Landsat 7 to Capture Minor Share of Data Market", Aviation Week & Space Technology, May 1, 1989, P. 89-90.

13. Gilmartin, Patricia, "USAF to Buy Used Boeing 707s For Use as Joint STARS Platforms", Aviation Week & Space Technology, Nov 12, 1989, P. 68.

14. Hobbs, David, Space Warfare New York: Prentice Hall Press, 1986.

15. Howard, William, "Satellites and Naval Warfare", Proceedings, April 1988, P. 40-50.

16. Kennedy, William A. and Marshall, Mark G., "A Peek at the French Missile Complex", Bulletin of the Atomic Scientists, Sept 1989, P. 20-23.

17. Kennedy, Col William V et al., Intelligence Warfare: Penetrating the Secret World of Today's Advanced Technology Conflict, Stanford: Crescent Books, 1987.

18. Krepon, Michael "Peacemakers or Rent-a-Spies?", Bulletin of the Atomic Scientists, Sept 1989, P. 13-15.

19. Larson, Jay L. and Pelletiere, George A., Earth Data and New Weapons, Washington, D.C.: National Defense University Press Publications, 1989.

20. Lenorovitz, Jeffrey M., "French Approval of SPOT 4 Ensures Earth Imaging Services Through 1990's, Aviation Week and Space Technology, Aug 14, 1989, P. 43.

21. Luongo, Kenneth N. and Wander, Thomas W., The Search for Security in Space, Ithica: Cornell University Press, 1989.

22. Marshal, Eliot "Space Cameras and Security Risks", Science, Jan 27, 1989, P. 472-473.

23. Rawles, James W., "Light Sat: All Systems Are Go", Defense Electronics, May 1988, P. 64-72.

24. Rawles, James W. "Military Satellites: The Next Generation", Defense Electronics, May 1988, P. 46-63.

25. Richelson, Jeffrey "Military Intelligence-SPOT is not Enough", Bulletin of the Atomic Scientists, Sept 1989, P. 26-27.

26. Shumway, Todd "A Tradition of Tactical Reconnaissance", Defense Electronics, Sep, 1989, P. 62-66.

27. Spector, Leonard "Keep the Skies Open", Bulletin of the Atomic Scientists, Sep 1989, P. 15-20.

28. Steinberg, Gerald M., Satellite Reconnaissance, New York: Praeger Publishers, 1983.

29. Torremolines, Spain, "France Defines Satellite to Complement SPOT Series", Aviation Week and Space Technology, October 23, 1989, P. 48.

30. The U.S. Army Command and General Staff College, Large Unit Operations, September 30, 1987.

31. The United States Naval War College Operations Department, Ambiguity and Command: Organizational Perspectives on Military Decision Making, (NWC 4195), 1986.

32. The United States Naval War College Operations Department, Collection of Information for Joint Forces,(NWC 3183), 1990.

33. The United States Naval War College Operations Department, The Greneda Operation, (NWC 4148), 1990.

34. Wilson, Andrew, "Earth Observation Space Segment", Interavia Space Directory, 1989-90, P. 517-555.

35. Zimmerman, Peter D. "Evidence of Spying", Bulletin of the Atomic Scientists, Sept 1989, P. 24-25.

Unpublished Sources:

36. Telephone conversation with MSgt. D. Armstrong of the U.S. Centcom Collection Management Staff, Tampa, Fla., 5 Dec 90.

37. Telephone conversation with Ms. H. McCormack of the SPOT Image Corporation, 1897 Preston Ave., Reston, Va., 7 Jan 91.

38. Interview with Mr. H. Westphal of the DMA Combat Mapping Support Center (CNC&S student), Washington D.C., 12 Dec 90.